MATERIALS SCIENCE

Cyrus C. M. Mody – *Maastricht University*

Joseph D. Martin – *Durham University*

Suggested Citation: Cyrus C. M. Mody and Joseph D. Martin, “Materials Science,” *Encyclopedia of the History of Science* (June 2020) doi: 10.34758/6afy-w006

Materials are everywhere. Imagine a common morning routine in the industrialized world. We arise from the synthetic sheets covering our memory-foam mattresses to cook our eggs in Teflon-coated pans while sipping coffee from ceramic mugs. We peer at newspapers through eyeglasses made from light-weight plastics with high refractive indexes. We commute to work in automobiles and trains crafted from bespoke alloys and coated in corrosion resistant paints. Every few minutes or so, we will glance at the shatter-resistant glass screens on our semiconductor- and lithium-ion-battery-powered smart phones. These substances, and the countless others that form the foundation of modern life, overwhelmingly trace their origins to the materials laboratories that proliferated in the mid-twentieth century. As a result, the field is an excellent probe of developments in the history of postwar science and technology, and of the material foundations of postwar life more generally. In exploring these developments, historians have emphasized materials science as an “interdiscipline” produced by distinct institutional rearrangements, which would later be replicated in the creation of bio- and nanotechnology.

WHAT IS A MATERIAL? WHAT IS MATERIALS SCIENCE?

Discussing the history of materials science requires grappling with the question of what constitutes a *material* in the first place. What distinguishes materials from mere matter? The venerable historian of metallurgy Cyril Stanley Smith posed this question in 1968, in the course of a lecture honoring the founder of the History of Science Society, George Sarton. A focus on *matter*, he determined, had promoted an atomistic—that is, reductionist—attitude that had dominated science for centuries. Atomism had proved fruitful for understanding the composition of matter, but it had done little to help people put matter to work. “Materials provide a good illustration of the difficulties of applying exact knowledge to a complicated world,” he wrote.[1]

Matter, in Smith’s way of thinking, encompasses all the stuff of the world. The science dedicated to understanding it has long focused on making the most general scientific claims

---

[1] Smith, “Matter versus Materials,” 637.

possible about its most elemental components. Materials, on the other hand, are those *arrangements* of matter whose properties make them conducive to human use. This meaning is rather obvious in languages other than English. German, for instance, refers to materials as *Werkstoffe*—substances that can do work. The properties of such substances can be discerned through careful observation, but they often resist easy explanation—not to mention prediction—in terms of the sorts of approaches developed for describing atoms and their constituents. Work and usefulness are inherently messy, human properties of materials that are not easily inferred from the properties of inert, non-useful matter.

This approach to distinguishing matter from materials means that whether or not something is a material is contingent. Meteoric iron—which can be found on the surface of the earth and therefore did not require mining and smelting technologies to access—has always been *matter*, but it only became a *material* when human beings picked it up and began to fashion it into jewelry, tools, and weapons. Designating a substance a material is a not just a claim about the substance itself; it is a claim about the relationship between the substance and its users, a relationship mediated by tools, techniques, and knowledge networks.

Image 1: The early phases of human civilization are identified by the materials characteristic of them—the stone age, the bronze age, and the iron age. This bronze-age (third millennium BCE) dagger, displayed at the Museum of Anatolian Civilizations in Ankara, Turkey, is crafted from meteoric iron and gold. The iron age refers to an era of widespread use of terrestrial iron, rather than meteoric iron, which is indicative of more sophisticated metalworking technology. Courtesy of Wikimedia Commons user Noumenon, reproduced in cropped form via the Creative Commons license.

Moreover, the use of materials does not require or imply a science of materials. The usefulness of a substance might lead us to ask questions about how it gets its useful properties, but answers to those questions are not prerequisite to fruitful use. In fact, as Smith observed, the complexity of many materials means that they often resist our attempts to understand them, even while we make use of them. Use has preceded theoretical understanding more often than not. Materials science shares this characteristic with the "engineering sciences" and fields such as thermodynamics, where useful human-made objects formed the basis for later scientific theorizing.[2]

But the difficulty of applying the methods of the physical sciences to materials has not prevented people from trying. Materials science emerged at the intersection of these two traditions: facility with the useful properties of matter on one hand, and a systematic approach to understanding matter, in all its complexity, on the other.[3] It was established with the goal of reversing the use–knowledge relationship, founded on the hope that our understanding of matter could guide the creation of new materials for specific uses. The circumstances that gave rise to this hope were characteristic of the Cold War.

COLD WAR CONTEXTS: MATERIALS SCIENCE EMERGES

Through the mid-1950s, Cold War competition focused principally on nuclear weapons development as the United States and the Soviet Union raced to amass larger and larger arsenals. But within the logic of nuclear deterrence, the delivery systems for nuclear weapons mattered just as much as the weapons themselves. A nation with powerful enough rockets could deliver a nuclear warhead to any spot it chose on the globe. The Soviet launch of the world's first artificial satellite, *Sputnik*, on October 4, 1957, therefore represented a shift. The aluminum sphere's radio blips were not as consequential as the demonstration of rocketry powerful enough to launch a satellite into space—or deliver a nuclear warhead. Some nuclear capabilities would still be based on nuclear-armed aircraft, and later submarines, but an increasing proportion of the nuclear powers' arsenals would sit on the tip of sophisticated rockets, ready to race toward their targets at a moment's notice.

Nuclear weapons, delivery systems (cruise and ballistic missiles and conventional and nuclear aircraft), and defensive networks all required new materials with exotic structural, thermal, and electronic properties. In NATO countries, but in the United States particularly, politicians, military leaders, and scientific administrators began to worry that insufficient understanding of materials represented a strategic shortcoming. That is, the problem was not just a lack of novel materials *per se*, but also a lack of the ability to place them within a coherent theoretical framework. Looking back a decade after *Sputnik*, in 1967, the Materials Advisory Board of the National Research Council could assert: "It is widely conceded now that characterization of the material is a major bottleneck in materials science."[4] Historians

[2] Hunt, *Pursuing Power*.

[3] Bensaude-Vincent, "Construction of a Discipline"; "Concept of Materials."

[4] Materials Advisory Board, *Characterization of Materials*, III-116.

have identified the perception of a materials "bottleneck" as the crucial impetus for the first institutional expressions of materials science.[5]

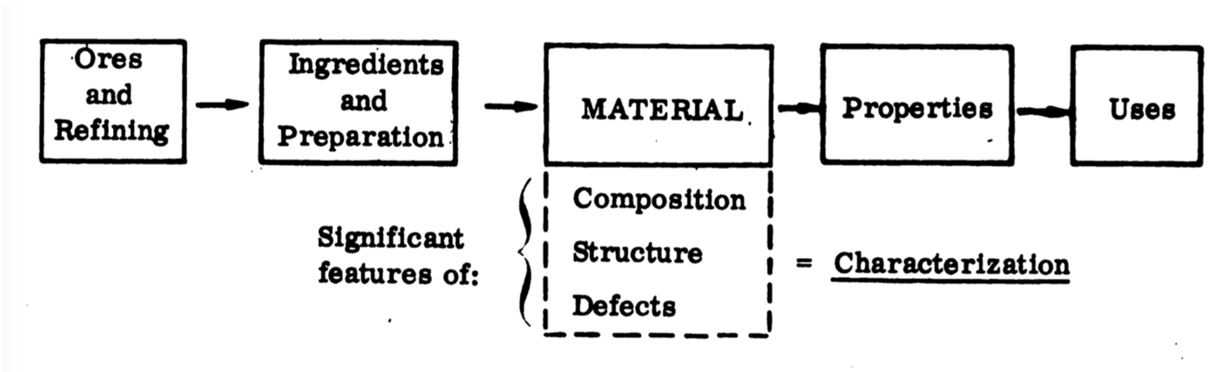

Image 2: This diagram in the Materials Advisory Board's 1967 report portrays characterization as a critical step on the road to effective use of materials. From Materials Advisory Board, *Characterization of Materials*, I-9.

Cold War antagonists perceived the need for new materials. But the fact that the materials bottleneck led to the emergence of "materials science" as a discrete institutional entity in the United States and then in Western Europe, but not in Warsaw Pact countries, tells us something about different conceptions of science and its purpose. In the Soviet Union, scientific work that collapsed any distinction between basic and applied science was held in high regard.[6] The ideologically justified, centrally planned system of science that emerged from the Bolshevik Revolution disdained "pure science," which was labeled bourgeois. Scientists interested in fundamental theoretical questions *could* prosper, but only if they formed ties with industry, navigated ideological minefields, and demonstrated their field's contributions to "state construction," for example by showing progress in nuclear weaponry.[7] Hence, there was no need for a Soviet "materials science," because scientists studying matter understood that they needed to take an interest in useful matter, that is, materials.[8]

North America and Western Europe could claim a long tradition of advanced research on useful matter, especially the metals used in the railroad, machine-tool, construction, and armament industries.[9] However, many Western scientists—the influential American physics community in particular—valorized "pure science" and sought to distance themselves from

[5] Stuart W. Leslie, "Profit and Loss"; Bensaude-Vincent, "Construction of a Discipline"; Mody and Choi, "From Materials Science to Nanotechnology"; Martin, "Name Change"; Choi and Shields, "Place for Materials Science."

[6] Josephson and Sorokin, "Physics Moves."

[7] Josephson, *Red Atom*; Pollock, *Stalin*.

[8] Josephson, "Soviet Scientists."

[9] Misa, Nation of Steel.

such practical outcomes of their work. As a result, abstruse research was more prestigious within the American physics community.[10] Naturally, the valorization of pure science did not entirely prevent American physicists from working toward practical outcomes. Especially during World War II, American physicists worked closely with metallurgists and other engineering scientists (see Manhattan Project). At war's end, though, the contributions of applied fields had to be kept secret, which allowed proponents of pure science to take the credit and to shape postwar military-funded science.[11]

The US defense establishment had little allegiance to pure science, of course—they wanted bombs, computers, and guided missiles. But physicists, who were overrepresented on the new committees formed to advise the military on scientific matters, convinced the generals that the way to get those things was for pure science to guide and discipline applied science. Even some prominent engineers, such as Vannevar Bush or Frederick Terman (Stanford's dean of engineering and later provost) believed that their disciplinary colleagues were backward and needed to take their cues from physics. Engineering disciplines such as metallurgy, on this account, were not capable of overcoming the materials bottleneck; for that you needed a *science* of materials.[12] As Robert Huggins, a prominent Stanford materials scientist, explained retrospectively to Congress in 1970, "the primary difficulty was not merely that more effort in materials technology was needed, but, instead, that much of what was being undertaken was not sufficiently grounded upon adequate scientific understanding of the physical phenomena involved." Moreover, according to Huggins, the deficit was not just in knowledge but also knowers: "one of the causes of this state of affairs was the fact that there were too few people available in this country whose technical training was sufficiently sophisticated with respect to the science of materials."[13]

The existing disciplinary architecture of American science was an impediment to the development of a science of materials because it allowed metallurgy and other engineering fields to remain beyond reach of the guiding hand of physics. The military's response to this problem was literally an architectural one. In order to break down the disciplinary barriers that kept scientists with a shared interest in materials apart, the Advanced Research Project Agency (ARPA), a division of the Department of Defense, funded a series of university-based laboratories that would bring them together.

ARPA had been founded in 1958 to undertake and fund research of strategic importance. A response to the materials bottleneck was one of its earliest undertakings. ARPA funding (with assistance from the Atomic Energy Commission and the National Aeronautics and Space

---

[10] Martin, *Solid State Insurrection*; Kevles, *Physicists*.

[11] Schwartz, "Making of the History"; Kaiser, "Atomic Secret."

[12] Leslie, *Cold War*, chs. 7–8.

[13] Huggins, "Accomplishments and Prospects."

Administration) established a series of what it called Interdisciplinary Laboratories (IDLs) on university campuses. The first three were launched at Cornell University, the University of Pennsylvania, and Northwestern University in 1960, with nine more funded in 1961 and 1962.[14] ARPA asked these universities to physically move their researchers with an interest in materials (in the early years, primarily physicists, chemists, metallurgists, and electrical engineers), and the tools they shared, into a common physical space. As planning documents from the era show, any new materials that came out of the IDLs themselves were of secondary interest; the main aim was to train a new generation of graduate students who would think of themselves as materials researchers first and foremost, and who would take that mindset with them into aerospace companies and other defense industries.

In 1962, as the first wave of IDLs was establishing itself, an administrative memo ARPA sent to them asserted: "You have to a great extent defined what is meant—at least in your university—by material sciences by listing in your proposals to us the names of individuals you believe to be the core of the program at your institution. The collective research interests of these individuals defines in more detail material sciences."[15] It would be an exaggeration to conclude that ARPA singlehandedly assembled materials science, but the IDLs fostered—and reveal in microcosm—a convergence that played out on a larger scale. The field that came to be called materials science consisted in a realignment of existing disciplinary expertise—mostly in physics, chemistry, metallurgy, and engineering—organized around the strategic aims of the Cold War.

In 1970, as materials science was becoming established as a new, interdisciplinary field, the US National Academy of Sciences commissioned an investigation into the history, present state, and future prospects of research on materials. The result, an expansive report consisting of four beefy volumes and a 250-page executive summary, was entitled *Materials and Man's Needs* and known colloquially as the COSMAT Report (for Committee on the Survey of Materials Science and Engineering).[16] It grappled with defining materials, settling on: "substances having properties which make them useful in machines, structures, devices, and products."[17]

But aside from this sprawling definition, which did not appear until chapter 3 of the report, COSMAT danced around the issue of precisely delimiting the term. "Materials," the report noted in its section on the nature of materials, "have a generality comparable to that of energy and information." They "are basic to manufacturing and service technologies, to national security, and to national and international economies" and "tend to be less

---

[14] National Research Council, *Advancing Materials Research*, 36.

[15] Quoted in Martin, *Solid State Insurrection*, 128.

[16] COSMAT, *Materials and Man's Needs*; *Materials and Man's Needs: Summary Report*.

[17] COSMAT, *Materials and Man's Needs*, vol. 1, 162.

proprietary than are the products made of them."[18] By the 1970s, materials scientists and engineers did not decide whether something was a material by comparing it to a definition; they rather assessed how it was embedded in systems of industrial production. Given the mélange of disciplines involved, each bringing its own understanding of materials, offering a consensus definition would have been difficult—so it is little wonder that materials scientists instead opted for an indexical definition-in-use.

Also notable about the language of the COSMAT report is the emphasis on economic relevance over defense relevance. Beginning in the late 1960s, many North American and Western European nations experienced economic and political turmoil, to which new science-based industries such as nuclear power, microelectronics, and (later) biotechnology were proffered as the solution. As tensions between the United States and the Soviet Union eased due to the politics of détente in the early 1970s, military justifications for science lost some of their power. It was in this environment that materials science crossed the Atlantic. Scientists in Western European institutions of basic research took up materials science as a way to make their fields relevant to the post-1968 healing of economy and society.[19]

The same shift occurred in the United States, but with complications wrought by the war in Southeast Asia. On the one hand, funding cutbacks meant the Department of Defense no longer prioritized the original aim of the IDLs, namely, to train personnel for defense industries. Instead, military planners began to pressure the IDLs to start producing battlefield-relevant new materials themselves. Yet contemporary reviews of military-funded research seemed to show that universities were not the most efficient place to put the Pentagon's money, if that was the goal. Thus, the military became disenchanted with its own creation. At the same time, public opposition to the war encouraged politicians to curtail the military's influence over science and encourage scientists to contribute to solving problems such as pollution, energy shortages, and poverty instead.

Thus when an amendment sponsored by Senator Mike Mansfield mandated that the military could only fund research directly relevant to its mission, the Department of Defense seized the excuse to transfer authority over the IDLs to the National Science Foundation (NSF) in 1972. There, they were renamed the MRLs (Materials Research Laboratories). Defense applications remained an important presence in the MRLs, particularly as protests against the war receded. But the MRLs—and the rapidly institutionalizing practice of materials science more generally—remained rooted in its legacy as an invented discipline, with goals defined by era-specific (and hence ever-evolving) challenges.

[18] COSMAT, *Materials and Man's Needs*, vol. 1, 67–68.

[19] Renn et al., "Research Program History."

A NEW TYPE OF DISCIPLINE

At its beginning, materials science was an example of a new way of organizing scientific labor that emerged during the Cold War: the interdiscipline. According to Paul Forman, "beginning in the late 1960s, the positive connotations that had been associated with the concept of a scholarly discipline throughout the first half of the twentieth century … died away in most minds concerned in any way with the creation, curation, or utilization of scientific or scholarly knowledge."[20] Materials science reflected dwindling confidence that existing disciplinary silos contained the stores necessary to confront the political and technoscientific challenges of the day. Disciplinary structures that had once been understood as foundations for progress came to be viewed as impediments to it.

Yet even as materials science exemplified this broader trend, it followed its own distinctive path. The features that set it apart are placed into relief when compared with another paradigmatic Cold War interdiscipline: cybernetics.[21] On the surface, the two have much in common. Both linked expertise from many established specialties. Both used that combined expertise to confront a shared set of problems—materials R&D problems in the case of materials science, the features and behavior of systems that rely on feedback mechanisms in the case of cybernetics. And both could do so because of the support of a powerful patron—ARPA and later the NSF for materials science, the Macy Foundation and later the Ford Foundation for cybernetics.

But beyond that, the similarities dissipate. In the case of cybernetics, the focal point of the interdiscipline was intellectual; it centered on the conviction that systems of many types, at many scales, and studied by many fields shared *structural* features. The impetus for materials science, on the other hand, was institutional. Although a few individuals, such as Arthur von Hippel at the Massachusetts Institute of Technology, had been pushing increased support for interdisciplinary collaboration around materials since the 1940s, the organic efforts of these individuals were insufficient to launch a movement of any scale or stability. Rather, the interdisciplinary structure of materials science was imposed from the top down by administrators and bureaucrats convinced that re-constellating the science and engineering disciplines was necessary to address a set of transient strategic aims.

Cybernetics, that is, formed from the bottom up, much more like a traditional discipline, into which practitioners are *disciplined* by being conditioned to approach a set of common problems in a particular way.[22] Materials science was constructed from the top down, through an institutional rearrangement of existing disciplinary practices. Cybernetics has received much more historical attention, and has sometimes been presented as an exemplar

[20] Forman, "On the Historical Forms," 92.

[21] Kline, *Cybernetics Moment*.

[22] Golinski, *Making Natural Knowledge*, 69.

Cold War interdiscipline because of its conceptual motives for rearranging scientific and technical expertise.[23] But top-down, commanded interdisciplines like materials science were actually more common in the history of postwar science, and more indicative of its guiding ethos. Notably, cybernetics fizzled out, whereas materials science, which was institutionally entrenched, not only survived but was used as a model for later interdisciplines such as nanotechnology. Because materials science was set in concrete—quite literally in the form of laboratories built on university campus—the ideological assumptions that informed its establishment continued to influence its character, even as it moved away from being a primarily defense-focused enterprise.

The rise of materials science roughly coincided with a parallel rise in systematic thinking about how both scientific knowledge and technology progress, and how they can be encouraged to interact more effectively. Vannevar Bush's manifesto *Science—The Endless Frontier*, penned in 1945, exerted considerable influence on postwar research policy. Distinguishing between "basic" and "applied" research, Bush articulated what would become an article of faith in postwar science policy: the latter could not thrive if the former were undernourished.[24] Basic research could be pursued and published openly, by university researchers, and the purported relevance of basic research to eventual technological development could be used to underwrite its relevance, with the added benefit of permitting "pure science" to accept military support while rejecting military classification.[25]

By the 1960s, the common wisdom in science policy circles was that research could be decomposed into three capacious categories: fundamental research, applied research, and development. This conviction underwrote what has become known as the linear model of innovation, the notion that implementation of new, strategically relevant technologies begins in fundamental research before it is applied and then, finally, implemented at scale.[26] Some historians have questioned the extent to which historical actors actually held this view.[27] Nevertheless, the general idea that healthy basic research was prerequisite to maintain a steady rhythm of successful technological development was built into the organization of many Cold War scientific institutions.

Many successful examples of materials science appeared at the time to uphold the linear model, at least superficially. Much of the Manhattan Project involved developing deeper understanding of the basic metallurgy of uranium and plutonium. The development of the

---

[23] E.g. Galison, "Americanization of Unity."

[24] Bush, *Science*.

[25] Daniels and Krige, "Beyond the Reach."

[26] Godin, "Linear Model."

[27] Edgerton, "Linear Model."

transistor at Bell Laboratories in 1947 rested on improved understanding of the electrical behavior of semiconductors, which spurred the realization that semiconducting devices could replicate the amplifying and rectifying functions of vacuum tubes. As the structures of macromolecules like proteins and DNA were uncovered, so too were clues about how to exploit those structures. The mid-century science of matter could boast a strong track record of transforming matter into materials. The interdiscipline of materials science grew from the assumption, inspired by this track record, that strategically urgent development efforts demanded greater input from basic science.

THE BUILT ENVIRONMENT OF MATERIALS SCIENCE

Physical space was itself perceived as a tool to spark fruitful interdisciplinary connection. Offices in Penn's Laboratory for Research on the Structure of Matter (LRSM), one of ARPA's first IDLs, were arrayed so that individuals with different disciplinary expertise, but similar topical interests, would be placed in close proximity. Instruments and tools were located in the center of the facility, and were to be shared among disciplinary groups, hedging against their being dominated by, or optimized for, one or another of them. What counted as successful interdisciplinary interaction within the LRSM, however, was vague. The laboratory produced few co-authored papers from people in different disciplines, although informal consultation was more common. Neither Penn nor the NSF, which had taken over administration of ARPA's materials laboratories in 1972, considered this a failure, however, and the LRSM would serve as a template for future interdisciplinary research centers, such as the Singh Center for Nanotechnology, which opened in 2013.[28]

[28] Choi and Shields, "Place for Materials Science."

Image 3: The Laboratory for Research on the Structure of Matter (left) next to the Singh Center for Nanotechnology at the University of Pennsylvania. Photo ©2018 by Brit Shields. Reproduced with permission.

As LRSM's story makes clear, these early materials research centers did not fully realize the interdisciplinary ambitions that animated them. Disciplinary training and identity run deep. Researchers who thought of themselves as physicists, or chemists, or engineers, were unlikely to abandon those identities. Disciplinary reward systems continued to determine their professional standing in the wider community, even if local incentives at their institution pushed them in collaborative directions. As a result, the IDLs were more properly *multi*disciplinary laboratories than they were *inter*disciplinary laboratories. And local considerations largely determined which disciplinary interests gained the upper hand at a particular facility.

An illuminating example can be found in the University of Chicago's Institute for the Study of Metals (ISM). The ISM, founded in the immediate aftermath of World War II, was not ARPA funded, but it served as one of the templates for the ARPA program and pursued a similar mission, bringing together physicists, chemists, metallurgists, and engineers whose expertise was relevant to the study of metallic substances. Its first director was Cyril Stanley Smith, who had been a physical metallurgist before his late-career transition to history of science. Under Smith's guidance, the ISM's staff struck a balance between physics and physical chemistry and conducted research squarely in the mainstream of postwar solid state science.

After Smith left in 1957, the ISM's strength in physics began to erode as key personnel left and, amid the 1960s funding crunch, were not replaced. By 1968, when the physical chemist Ole J. Kleppa took over the directorship of what was now called the James Franck Institute (JFI), the bulk of the staff were chemists, and he recognized the need to replace the institute's lost capacity in physics. The addition of two staff in particular, Leo Kadanoff in 1978 and Albert Libchaber in 1982, would shift the JFI's emphasis. Instead of physical chemistry and metallurgy, more resources flowed toward the study of critical phenomena (such as phase transitions) and non-linear dynamics (such as fluid flow and turbulence). The JFI subsequently became a recognized leader in these emerging areas of condensed matter physics.[29]

Although the topical emphasis of these multidisciplinary laboratories could shift quite easily, their mode of research was remarkably consistent. Cornell's materials research laboratory, for instance, maintained a stable organizational mode amid broader changes in the local institution and wider national context. These laboratories pioneered a "center model," which grouped together researchers from multiple disciplines in a single site focused on a strategically relevant research theme. This model of laboratory work grew in prominence later in the twentieth century, despite a spotty track record promoting genuinely interdisciplinary research. The reasons are several. For individual researchers, these centers represented a reliable source of support, access to up-to-date equipment, and some relief from the constant pressure to seek support for their research. For universities, they were a magnet for external funding, a source of prestige, and a potent recruiting tool. Government funders, for their part, continued to view such installations as an effective solution to evergreen concerns about international competitiveness.[30]

On the local level, that is, these interdisciplinary centers' emphases continued to be driven by disciplinary concerns. On a larger scale, however, the proliferation of these centers created a network of institutions with shared objectives and modes of operation. The stability of this peer group of institutions dedicated to materials science assured that the new field had a firm, reliably funded interdisciplinary platform, even if individual laboratories could be disciplinarily fractious. The faith ARPA showed that disciplinary boundaries could be orchestrated from the top down met its limits when it reached the level of individual researchers, but it was not entirely misplaced insofar as the institutional structure it enabled sowed a seed from which a more enduring disciplinary practice could begin to grow.

---

[29] Martin, *Solid State Insurrection*, 232–34.

[30] Mody and Choi, "From Materials Science to Nanotechnology."

STANFORD: A CASE STUDY

As the Penn and Chicago examples show, different locales found site-specific ways to enact the top-down interdiscipline of materials science. Yet each particular site also had to respond to national and international trends. The overall effect resembled an amoeba: the main body of the materials science amoeba moved by catching up to the pseudopods that grew from its margins. To get a sense of how the amoeba of materials science locomoted in its second phase, starting in the late 1960s, we now look at one of its most important pseudopods, Stanford University. Stanford generally has been a favorite test object of historians of postwar US science and technology because of its influence on other sites, its proximity to (and supposed stimulation of) Silicon Valley, and its deep archival holdings. Although some aspects of Stanford's influence have been exaggerated, its status as role model for materials science is hard to contest. When the Metallurgy Department became the Materials Science Department in 1961, it was the second in the world, after Northwestern University's, to adopt that name. That same year, Stanford's Center for Materials Research (CMR) received second-wave IDL funding.

By 1970, the logic of science and defense policy that had inspired the CMR along with the other IDLs/MRLs was beginning to dissolve. At least in the United States, the view that applied scientists needed to learn at the feet of basic research was no longer as convincing as it had been in the late 1950s. One symptom was that departments that had converted from "metallurgy" to "materials science" in that earlier era now started to change their names once more: not back to metallurgy but, as was the case at Stanford, from "Materials Science" to "Materials Science and Engineering" (MSE). By that time there were some twenty-eight departments at American universities with "materials science" in their name; about 40% of North American colleges of engineering hosted such departments.[31]

That is, in less than ten years the field had expanded well beyond the Materials Research Laboratories. Yet even as the MRL model inspired developments at other universities, it was also being called into question. In 1972, as the MRLs were being transferred from ARPA oversight to the NSF, the NSF commissioned a site review of its new charges. The review concluded that:

1. Research in progress is in many cases not materials research
2. Research in progress is often not interdisciplinary

[31] Joseph M. Pettit, letter to Richard W. Lyman, October 20, 1970, re: Name Change for Materials Science Department, Lyman Papers, Box 65, Folder MSE.

3. Materials science is stressed more than materials engineering[32]

This was a problem because, by 1970, the inclination of Congress and the Nixon administration was (or at least Stanford's materials scientists believed it to be) "to allow the universities to 'cleanse themselves by fire'—i.e., suffer, and to cut off the academic fat cat professors who 'really don't produce anything of value for this country anyway.'"[33] Basic science was out of favor, whereas academic engineering science and other research activities that looked applied enough to "produce anything of value for this country" were on the rise. Materials scientists who had struggled in the 1960s to appear properly scientific now had to turn around and pass themselves off as engineers. Materials science—created as an interdiscipline—was now being rebranded as an ally of the discipline of engineering.

Stanford regularly sent emissaries to Washington, DC, to confer with executives at the major federal funding agencies. The message Stanford received was to follow the buzzwords, whatever those might be at the moment. For example, in 1974 they heard that the trendy directions were "'biological engineering' and 'scaling factors' in bringing laboratory and small-scale results into large-scale use [such as] microfabrication in electronics."[34] But they were also apprised that, amid the debates about overpopulation and resource scarcity of the early 1970s (and especially after the oil shock of 1973), federal agencies' "priorities run to energy (naturally) and natural resources including food and minerals."[35] Particularly after the founding of the Energy Research and Development Administration (ERDA) in 1975, Stanford eyed possible materials science applications in solar and nuclear energy. They also developed proposals for research on catalytic materials, superconducting materials for long-distance electricity transmission, and other energy conservation applications. And amid the economic turmoil of the mid-1970s, Stanford scientists benefited from the Ford administration's view of "science and technology as a solution to our current inflationary problems [such that] scientific R&D will be … protected from the President's budget cuts."[36]

These cues show that materials science had moved beyond its Cold War origins and reliance on the national-security state. But the chaotic environment of the early 1970s gave materials scientists at Stanford and elsewhere no clear indication of who the next reliable patron

---

[32] R. J. Wasilewski (section head, Materials Research Laboratory section, National Science Foundation), letter to Robert Huggins (director, Stanford Center for Materials Research), February 2, 1972. Stanford Sponsored Projects Collection, Box 14, Folder "Center for Materials Research."

[33] Peter Carpenter (assistant director CMR), "The 1970 Military Authorization and Appropriations Bills and the Fulbright (Mansfield) Amendment," circa January 14, 1970. Stanford Sponsored Projects Collection, Box 14, Folder "Center for Materials Research."

[34] William Massy to file, February 3, 1975, Lyman Papers, Box 125, Folder "National Science Foundation."

[35] Ibid.

[36] Massy and Devaney, memo to file, June 19, 1974, Lyman Papers, Box 125, Folder "National Science Foundation."

would be. True, the MRLs had moved under the NSF's umbrella, but indications appeared that the Foundation was unhappy with taking orphans from the military, and that it was likely to lose some of its portfolios to ERDA and other agencies. Even if the NSF continued funding the MRLs, federal support now came with a variety of unwelcome strings. If the Center for Materials Research and the other MRLs were to continue, therefore, they would need to find a more efficient way of operating so as to make more use of less money.

Yet for all the era's challenges, the MRLs had much going for them. As William Massy, Stanford's vice provost, reported to his colleagues later that year, "The Materials Research area is hot, not just in energy-related areas, but in areas relating to conservation, etc. Metallurgy is of particular interest right now." Interdisciplinarity itself was also "hot." The CMR had been founded during a twenty-year postwar stretch when the number of degree-granting interdisciplinary centers at Stanford was growing by about one every seven years. In 1969, the year of peak campus protest, that number doubled, and for almost the next twenty years it grew at a rate of one *per year*.[37] Where the CMR had been a strange bird at its founding, by the 1970s it was a model to be followed.

Followed *and* partnered with. What scientists at Stanford, Cornell, MIT, and elsewhere soon figured out was that if their campus had an MRL, then it made their proposals for other kinds of centers more attractive; and when those centers were built, their partnerships made the MRLs more sustainable. Nationally and internationally, the MRLs formed a network that gave rise to the trappings of a mature discipline; locally, they formed networks that expanded the reach of that discipline into new materials and new tools. At Stanford and Cornell, for instance, the MRLs helped local synchrotron scientists and microfabrication experts gain center funding in the 1970s.[38] The tools that those centers could offer in turn became justifications for the NSF to continue funding the Stanford and Cornell MRLs. And the full suite of tools that those MRLs could offer to users became a justification for a new set of disciplines—such as geology, computer science, chemical engineering, and especially the life sciences—to join forces with materials science and with the disciplines that were already party to it (electrical and mechanical engineering, metallurgy, physics, surface science, and inorganic and analytic chemistry).

In other words, materials science grew by turning a threat into an opportunity. The lean and contentious years of the 1970s forced materials scientists to diversify in multiple ways: to find new patrons as military funding became thinner and more politically contested; to find adjacent fields with new tools for materials scientists to use, the costs of which could be shared broadly; and to find new areas of application and new disciplines with which to collaborate. As a result, the instrumentarium of materials science grew and the range of materials the field studied gradually expanded beyond crystalline metals and

[37] Nelson, "Cacophony or Harmony?"

[38] Mody, *Long Arm*, ch. 4; Hallonsten, "Parasites."

semiconductors to include amorphous materials, ceramics, polymers, and (at the margins) biomaterials.

MATERIALS SCIENCE COMES OF AGE

The story up to this point has mostly been an American one. This is not because research on and understanding of materials was a predominantly American phenomenon. Research on materials was a global undertaking, but grouping that research together in a particular way and calling it materials science was a contingent historical process that first unfolded in the United States.[39] The name, and some of the field's core ideas, were then carried elsewhere to integrate with local traditions. As Johan Gribbe and Olof Hallonsten put it in their history of materials science in Sweden, for instance, "Swedish materials science was not imported from the United States into a vacuum. … But there is a clear historical distinction to be made: the research on materials in Sweden prior to the 1970s, which took place in industrial research institutes and technical universities and was mostly oriented to the needs of the wood and iron industries, differs from the cross-disciplinary materials science that emerged and established itself gradually in Swedish universities in the 1970s."[40] In Sweden, as elsewhere, the label "materials science" was largely promoted by entrepreneurial scientists who had spent time in the United States. And the label did real work: it helped those scientists reconfigure local ways of doing materials research to include new tools, materials, applications, and systems of funding.

As both the Stanford and Swedish cases indicate, institutional developments required more than buildings and money. Scientists are also disciplined by their training and by profession-level reward systems. The establishment of materials science as a distinct entity in the landscape of American science therefore required the emergence of both a set of organizations that could confer a sense of professional validation, and a generation of researchers trained to be validated by them. The founding (or name-change) of materials science departments satisfied the second requirement, while the establishment of the Materials Research Society (MRS) in 1973 went a long way toward achieving the first.

In some ways, the Materials Research Society responded to the growth of an interdisciplinary academic specialty nurtured in the MRLs, of which there were fourteen in 1973 (with two more to be established in 1974). But the society's founders also meant it to be a home for materials scientists in industry and government (many of whom, as ARPA had intended, had passed through the MRLs at some point in their careers). The aim to represent physical scientists outside academia was not unique to the MRS but it was also not shared uniformly by peer organizations. The American Physical Society, in particular, remained staunchly

---

[39] Cahn, *Coming of Materials Science*; Bensaude-Vincent, "Construction of a Discipline;" Hentschel, "Von der Werkstofforschung."

[40] Gribbe and Hallonsten, "Emergence and Growth."

academic and actively resisted efforts to increase representation for its members employed in industry. However, other organizations under the American Institute of Physics umbrella, such as the American Vacuum Society or the American Geophysical Union, were friendlier to industrial members. The American Chemical Society, meanwhile, was quick to embrace its industrial relevance. Its division of Industrial and Engineering Chemistry was the first such technical division to be established in 1904, and many industrial chemists held positions of influence within the society throughout the twentieth century.

But even those societies that embraced industrial interests remained squarely disciplinary in their focus. The MRS promised to champion the professional interests of industrial, as well as academic and government researchers, without also imposing any particular disciplinary orthodoxy. That openness helped the MRS recruit. A little over a decade after its founding, the MRS had several thousand members and had established its own peer-reviewed publication, the *Journal of Materials Research*.[41] The MRS's strategies and growth reveal the conviction among its early leaders that contact between researchers from multiple disciplines was not sufficient to sustain interdisciplinary research—that interdisciplines required the same sort of apparatus as disciplines themselves, namely professional organizations to confer a sense of belonging, meetings and symposia to facilitate communication, and journals to showcase the latest research.

Whereas materials science in its institutionalized form had been largely an American phenomenon during the early Cold War, it became global in the 1970s. That is to say, long-standing local scientific traditions that were oriented toward understanding and applying the properties of materials now began to rearrange along the lines of materials science in the United States. However, the institutional environments in which materials science took root differed regionally. Before World War II, the United States could boast very little centralized support for scientific research. Universities were private or funded by individual states, industrial laboratories operated according to their own interests, and federal institutions like the National Bureau of Standards tended to be small or, like the Smithsonian Institution, maintained through private endowments. The new postwar federal enthusiasm to fund scientific research therefore confronted a relatively clean slate, upon which an institutional structure could be built that responded directly to its immediate priorities.

In many European nations, in contrast, state-sponsored research organizations, including university systems, had long been important contributors to national interest and identity. At least initially, Western European and American elites agreed that European research institutions should be guided toward basic research after the war.[42] In West Germany, the Kaiser Wilhelm Society was renamed the Max Planck Society for the Advancement of Science (*Max-Planck-Gesellschaft zur Förderung der Wissenschaften*) and given a greater focus on basic

41 Phillips, "Founding of the MRS."

42 Krige, *American Hegemony*.

research. In the early postwar years, new MPG institutes were directed toward fundamental topics, while the Society's pre-war applied institutes were allowed to wither.[43]

Similarly, in Japan, existing structures of university research prevailed after the war, until the centrally planned efforts of the 1970s and 1980s, such as the construction of Tsukuba Science City, co-located researchers from many disciplines in the spirit of the IDLs, hoping to catalyze innovation on a grand scale.[44] And China maintained a focus on metallurgy—a historical strength—much longer than the United States. The Shenyang National Laboratory for Materials Science was established in 2000, and it is still administered as part of the Institute of Metal Research of the Chinese Academy of Sciences.[45]

The name materials science and its cognates were therefore not immediately adopted by European or Asian scientific communities, as there was no urgency for fundamental science to guide the search for applied solutions to problems similar to the "materials bottleneck" in the United States. However, the primacy given to fundamental science in the rebuilding of Western European research institutions laid the groundwork for the eventual adoption and adaptation of the American model for materials science there.

In the Max Planck Society, for instance, much of what could be classed as materials science occurred within the Fritz Haber Institute (FHI), which had historically been devoted to physical chemistry.[46] At the FHI, an increasing focus on solid state physics (*Festkörperphysik*) and surface science (*Oberflächenphysik*), began to emerge in the late 1960s, in tandem with the slowing of the economy and high-level policy initiatives to stimulate science-based industries. It is in that economic and policy context that we should see the shift at FHI as catalyzing closer links between traditional engineering approaches to materials and basic physical and chemical investigations.

That shift was eased by the readiness of the materials science model, as indicated by the 1973 publication of the textbook *Werkstoffe: Aufbau und Eigenschaften* (*Materials: Construction and Properties*).[47] But the adoption of the vocabulary of materials science was itself fostered by the postwar "instrumental revolution" in which new microscopy and spectroscopy tools upended traditional fields like metallurgy and structural chemistry.[48] For example, Ernst Ruska, the pioneer of electron microscopy, had established his research group at the FHI in

---

[43] Renn et al., "Research Program History;" Sachse, "Basic Research."

[44] Bloom and Asano, "Tsukuba Science City."

[45] Plummer, "Metallurgy Is Key."

[46] James et al., *One Hundred Years*.

[47] Hornbogen, *Aufbau und Eigenschaften*.

[48] Renn et al., "Research Program History," 55; Morris, "Sites and Technology."

the 1950s, and through the 1960s enjoyed a great deal of autonomy to pursue his program of instrument development.[49] The electron microscope in particular underwrote a new interest in surface science, which addressed basic questions about chemical and electrical interactions at surfaces while also providing urgent applied know-how for the semiconductor industry.

New tools were also a vector for materials science–esque constellations of expertise in France. A country with a rich chemical tradition, France pursued much of its postwar research on materials under the heading of solid state chemistry (*chimie du solide*), and within the rigid, hierarchical structures provided by the Centre National de la Recherche Scientifique (CNRS) and the university system.[50] A timely development came in 1967, when the French and German governments agreed to establish the Institut Laue-Langevin (ILL) in Grenoble. The ILL was built around a nuclear reactor optimized to generate high neutron fluxes.[51] Because neutrons do not carry an electrical charge, they are not deflected by the electrons surrounding atomic nuclei, and so are effective probes for diffraction experiments.

The ILL began operations in 1974, with the United Kingdom as a third partner. It arrived just as the United States was ceding its leadership in neutron facilities. The High Flux Beam Reactor at Brookhaven National Laboratory (BNL) and the High Flux Isotope Reactor at Oak Ridge National Laboratory had paced neutron diffraction research through the early 1960s, but were growing long in the tooth. Plans for a next-generation neutron source hosted at Argonne National Laboratory were scrapped in 1968, amid tightening federal budgets and a decision to focus funding for large facilities on high-energy particle accelerators.[52] Europe claimed the global lead in neutron diffraction research just as it was becoming more pertinent for materials research, leadership it would retain as large research facilities became increasingly oriented toward the needs of small-science investigators like materials scientists in the 1980s and 1990s.[53] At around the same time, European facilities similarly ascended to the top rank in materials research using synchrotron radiation.[54]

The model of materials science that first emerged in the United States was a loose alliance, held together by top-down institutional pressures. But, as is the case with materials themselves, enough pressure over enough time can cause a system to shift to a new stable arrangement. The slowing of Western economies around 1970 provided the motive for such

---

[49] James et al., *One Hundred Years*, 160–69.

[50] Teissier, "Solid-State Chemistry."

[51] Hallonsten and Kaiserfeld, "Neutron Sources."

[52] Rush, "US Neutron Facility Development."

[53] Crease and Westfall, "New Big Science."

[54] Hallonsten, "Parasites"; Heinze, Hallonsten, and Heinecke, "From Periphery to Center" and "Turning the Ship."

a reconfiguration of materials science in the United States, and the adoption and adaptation of materials science in Western Europe. But change requires means and opportunity as well as motive; those were largely provided by transnational communities of practice, particularly those oriented around tools.[55] By the 1970s, materials science was becoming a global phenomenon, in part because of the way the instrumental expertise associated with it flowed freely across borders.

The global materials science community began focusing on new types of materials in the 1970s as well. When the field began to emerge in the late 1950s and early 1960s, it cleaved closely to its metallurgical roots. The US National Research Council's Materials Advisory Board had grown out of an earlier Minerals and Metals Advisory Board. Similarly, Lawrence Van Vlack's foundational 1959 textbook *Elements of Materials Science* focused squarely on the sorts of techniques used to characterize and manipulate metals. But as materials science matured in the 1970s and 1980s, new types of materials gained prominence. Semiconductors had been of keen interest for some time, but became even more central with the advent of consumer computing. As the features etched into computer chips shrank ever smaller, semiconductor manufacturers began putting more emphasis on thin films and other "sub-micron" architectures of materials. New techniques in physics and chemistry paved the way for better understanding of amorphous solids, which went hand in hand with a focus on glass, ceramic, and other disordered materials. The first viable fiber optic cable was developed at Corning Glass Works in 1975 and IBM researchers observed high-temperature superconductivity in ceramic materials in 1986. And plastics, suddenly, were everywhere.

It is helpful to think about this transition in terms of infrastructures. The infrastructures of the mid-twentieth century were largely metallic, a fact that is evident from the conduct of World War II. It has been called "the physicists' war," but it might just as accurately be called "the metallurgists' war."[56] In the civilian world, infrastructures founded largely on metallurgical knowledge fundamentally transformed the world between 1860 and 1960. Rail, automobile, steamship, and civil aviation networks changed the way people and goods traveled. Advanced metallurgical knowledge was required for the rails that trains traveled on and the boilers of the steam engines powering trains and steamships. Later, the first airplanes were largely made of wood and cloth, but the aviation industry perceived metal as the material of the future and therefore replaced such "pre-modern" materials even when there was no advantage in doing so.[57] Similarly, the metal wires of the electrical grid and the metal pipes of widespread centralized waterworks transformed daily life and health. The telegraph cables that crisscrossed the globe—although critically dependent on expanded

---

[55] Mody, *Instrumental Community*.

[56] Kaiser, "Blackboards."

[57] Schatzberg, "Ideology and Technical Choice."

understanding of insulators and dielectrics, they were metal at their core—radically altered international communication.

Image 4: Metal infrastructure: The Forth Rail Bridge shortly after its opening in 1890. Spanning the Firth of Forth near Edinburgh, the bridge was completed in 1889 and came to symbolize British industrial prowess. Courtesy of Wikimedia Commons.

In the late twentieth century, the material composition of these infrastructures began to shift, ever so subtly. Metals were, of course, still central, but where these systems were changing, it was often because of the encroachment of non-metallic materials. Pre-war, a few plastics such as celluloid, bakelite, and nylon began to substitute for natural materials; with the postwar shift to oil feedstocks, plastic production took off and space-age plastics began to replace metals (for instance, Kevlar for armor and PVC for water pipes).[58] Carbon fiber compressor blades were deployed in jet engines. The telephone network was gradually transistorized. Telegraph cables were abandoned at the bottom of oceans and fiber-optic cables were run in their place. And computerized control systems became essential for managing these increasingly complex networks.

[58] Mercelis, *Beyond Bakelite*; Travis, "Modernizing Industrial Organic Chemistry."

Taking the infrastructural perspective makes it clear why materials science succeeded as a stable, international field, even though it fell short of ARPA's early interdisciplinary ambitions. Materials—critically, *new* materials—became essential components of the systems that made the world work in the second half of the twentieth century. That meant that polymer chemists, physical metallurgists, and semiconductor physicists, though they might work very differently and speak very different languages, had ample reason to talk to one another when they found their expertise coordinated within the same systems.

THE END OF THE COLD WAR AND THE RISE OF NANO AND BIO

The academic center (usually so-named but sometimes called a laboratory, institute, or facility) was a particularly influential organizational model in materials science. The importance of centers distinguishes materials science from traditional disciplines (which usually rested on chairs or departments); but it is a feature it shares with other postwar interdisciplines. Indeed, it is difficult to say whether other interdisciplines followed materials science in adopting centers or whether other centers gave rise to interdisciplines in the same way as the Materials Research Laboratories. Particularly from the mid-1970s onward, the success of the MRLs in navigating the budgetary, administrative, and political turbulence of the early 1970s cemented the center model as *the* go-to science policy instrument, flexible enough to shift with changing political climates and address new social problems.

Thus, whatever problems state-sponsored science was asked to solve after 1975, at least in Western Europe and North America, centers were offered as part of the solution: aiding ailing industries; bringing industrial principles, personnel, and practices into the academy; helping voters live longer, healthier lives; addressing social inequalities; creating more resilient organic and built environments; fighting terrorism—all these, and more, were social problems with which academic centers were tasked in the late and post-Cold War eras.

In the go-go 1980s, the Reagan administration tasked the National Science Foundation with bringing American academic researchers into closer contact with industry with a long-term view to weaning universities off of federal support. To that end, in 1984 the NSF established funding for a slate of Engineering Research Centers supporting academic research relevant to industries such as microelectronics, textiles, and automobile manufacturing.[59] The ERCs were explicitly modeled on the MRLs and on earlier centers based on the MRLs model. Together, the MRLs and ERCs gave rise to cascades of center programs: the Science and Technology Centers and the Centers for Research Excellence in Science and Technology programs in 1987; the Materials Research Science and Engineering Centers (the next iteration of the MRLs) in 1994; the Nanoscale Science and Engineering Centers in 2001; as well as a variety of smaller center programs and one-off centers not contained within a larger program. It was in this milieu that materials science passed into the post-Cold War era.

[59] Belanger, *Enabling American Innovation*.

The end of the Cold War brought a series of reorientations of science policy in many countries—usually changes that were already underway in the 1980s or even 1970s but that accelerated with the end of superpower confrontation. First, the physical sciences that had gained power and prestige from their association with Cold War weaponry quickly lost favor to the life sciences. If materials science had emerged in the 1990s rather than the 1950s, it would likely have seen metallurgists sitting at the feet of biologists rather than physicists. As it was, centers and facilities that had linked materials research to the physical sciences underwent what Park Doing calls a "velvet revolution" in which leadership and application focus shifted to the life sciences and biomedicine.[60]

Second, the Cold War mode of "Big Science"—giant, centralized organizations with enormous sunk costs, such as particle accelerators and space stations—also lost favor, replaced by decentralized networks of small, nimble research clusters. This shift reinforced the tilt away from the physical sciences toward bio, as exemplified by the early 1990s failure of the (large-scale and centralized) Superconducting Super Collider and the triumph of the (networked and decentralized) Human Genome Project.[61] As a result, center programs such as the MRLs began to emphasize the "center" part less and the "program" part more: that is, their leaders and funders presented them as networks of institutions, with each node in the network itself formed from a local network of disciplines, centers, facilities, and tools.

Third, the world economy globalized and liberalized. One effect was that businesses adopted the network model, and the centralized business behemoths that dominated the twentieth century (such as IBM, Philips, Siemens, General Electric, and Imperial Chemical Industries) fractured. Some of the giants that had been most involved in materials research, such as RCA and AT&T, folded entirely. Many of the rest withdrew from long-range and fundamental research, leading to a large-scale migration of industrial materials scientists into academia—bringing with them perspectives and contacts oriented to business, and little allegiance to traditional disciplinary boundaries. The interdisciplinarity that materials science had done so much to foster was once more in vogue.

All these shifts co-evolved with changes in the content—and not just the organization—of science. For one thing, the instrumental revolution continued apace, with entirely new classes of instruments such as scanning probe microscopes appearing in the 1980s. As academic research became more commercially oriented, many of these new instruments formed the basis for start-up companies founded by professors and/or their former students. Also, advances in computing made possible by materials science now provided new computational tools for *doing* materials science. The creation of new materials and

[60] Doing, *Velvet Revolution*.

[61] Kevles, "Big Science."

exploration of their properties *in silica*—a dream of early promoters of materials science such as John von Neumann and Arthur von Hippel—gradually became a reality.[62]

One development that many science policymakers and policy-minded scientists latched onto was the converging size scale at which a range of disciplines focused their attentions. Over several decades, the size of the smallest features that could be manufactured in solid media had been declining; in the semiconductor industry this trend is known as Moore's Law, but it has cognates in other fields. Over the same period, the largest macromolecules that chemists and biologists could manipulate (and computer scientists could simulate) grew steadily. By the 1990s, researchers working from these opposite directions were starting to meet in the middle, at a size scale in the tens of nanometers—exactly the size scale where many of the new instruments of the 1980s (such as the scanning tunneling microscope) and improved versions of older instruments (such as electron microscopes) operated.[63]

Thus, over the 1980s and 1990s, the prefix "nano" diffused through a variety of fields and research organizations. By the early 1990s, there were enough adopters of the nano label that they could see each other and start to form connections. And by the late 1990s, nano promoters in many nations could offer that label as the organizing principle by which science could become more interdisciplinary, more commercial, more efficient, and better able to solve a range of social problems.

In some countries and subfields, materials scientists were early adopters of nano. Herbert Gleiter in Germany, for instance, was one of the first to speak of "nanostructured materials."[64] Elsewhere, such as the United States or Switzerland, the lead in promoting nano was taken by surface scientists or mechanical engineers or people associated with scanning probe microscopes or other instruments capable of exploring the nanoscale.[65] Yet these other fields were already entangled with materials science through institutions such as the Materials Research Science and Engineering Centers or the Materials Research Society. And when various national nanotechnology initiatives began to form around 2000, materials scientists, their organizations, and the organizational model with which they were associated were all quickly enrolled. In the Unites States, at least, having a MRSEC conferred an enormous advantage in acquiring a "nano" center or facility; and having a nano facility boosted the productivity of the MRSECs.[66]

---

[62] Bursten, "Computer Simulations."

[63] Rohrer, "STM: 10 Years after."

[64] Nordmann, "Invisible Origins."

[65] Mody, *Instrumental Community*; Merz and Biniok, "Local Articulation."

[66] Mody, *Long Arm*, chs. 5–6.

The most recent transition in the ambit of both nano and materials science has been the rise of (nano)biomaterials. In the first years of the national nanotechnology initiatives, biomaterials were marginal. Indeed, one reason given in the United States for founding a national nanotechnology initiative was that it would compensate for the physical sciences' losses of funding and prestige to the life sciences over the course of the 1990s. But with time, bio came to suffuse both nanotechnology and materials science, for reasons that are simultaneously political (voters want to live longer and healthier) and scientific (the line between a "material" and a living tissue has blurred considerably).

Of course, the use of materials in medicine is not new, and even the language of "biomaterials" dates to the late 1960s and early 1970s, when materials scientists, many of them based at the proliferating materials science centers, institutes, and departments, began collaborating with nearby medical schools.[67] That language became substantially more prominent, however, in the twenty-first century—a recent survey noted an approximately six-fold increase in "biomaterials" and similar terms between 2000 and 2012.[68] The reasons are several. First, biological systems were a natural frontier for the nanoscale research that had blossomed in the 1990s. The Cold War sense of mastery over nature at its smallest scales had impelled hopes for manipulating human biology directly at the level of cells and molecules, as attested to by the hit 1966 film *Fantastic Voyage*, in which a miniaturized submarine and its crew are injected into a stroke victim to repair the damage in his brain. Advances in science at the nanoscale, which corresponded to the scale on which many biological processes occur, along with attention to the physical features of biological systems themselves within the new subspecialty of soft matter physics, have reignited that optimism and encouraged research into the medical applications of nanotubes, nanogels, quantum dots, and other minute materials. Indeed, *Fantastic Voyage* has itself had a second life as a means of assimilating young nanoscientists.[69]

---

[67] Horowitz and Torgesen, *Biomaterials*.

[68] Zadpoor, "Evolution of Biomaterials Research."

[69] York, "Nano Dreams."

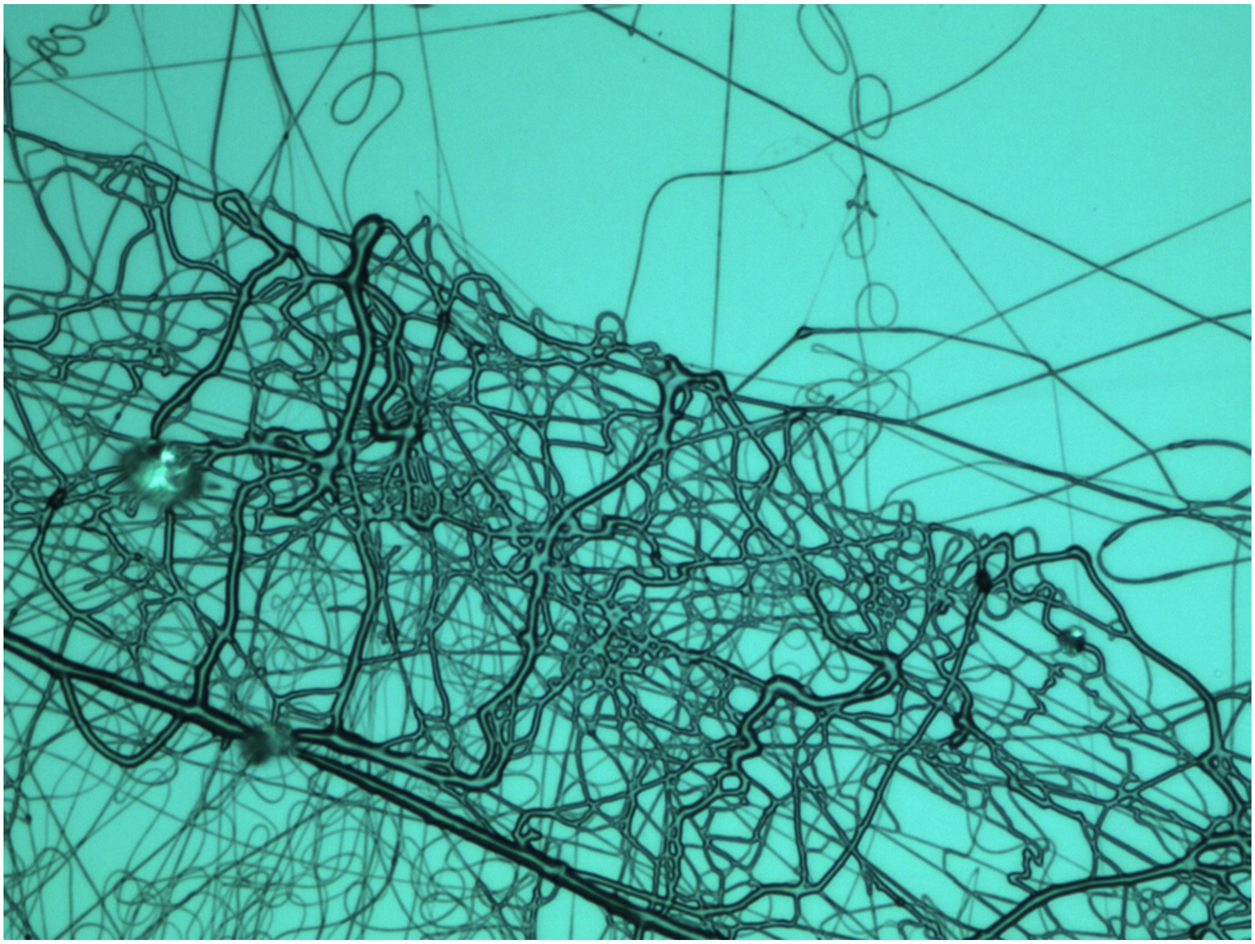

Image 5: Electrospun nanofibers made of synthetic materials, such as these polyurethane nanofibers, are used in biomedical applications such as tissue engineering and drug delivery. Courtesy of Wikimedia Commons user Wikicristof, reproduced via the Creative Commons license.

The second reason for the shift towards biomaterials is a shift in how both physicians and materials scientists think about how materials interact with the body. Whereas older materials-based medical interventions such as prostheses, implants, and the pacemaker focused on making materials as inert as possible within the body, modern biomaterials often seek out substances whose properties work in conjunction with biological processes.[70] Modern dissolvable sutures, for instance, are made from polymers that break down into lactic acid, which is flushed from the system by natural metabolic processes. Bioactive materials are also commonly used for drug delivery and in scaffolds for tissue regeneration. Even traditional metallurgy has been stimulated by the bio imperative. For instance, where metal hip implants once had an expected lifetime longer than their recipients', today's

[70] Huebsch and Mooney, "Inspiration and Application."

population needs implants earlier and then lives longer than the previous generation—meaning that traditional implant alloys wear out before their users do.

The third factor is institutional. Physics commanded tremendous prestige during the Cold War. As the Cold War drew to a close, however, biology was overtaking physics in prestige, as exemplified by the failure of the Superconducting Super Collider in the United States just as the Human Genome Project was gaining momentum.[71] With more funding flowing from the National Institutes of Health, and from the biotechnology companies that had sprung up in the wake of changes to patent law in the 1980s,[72] the always-nimble field of materials science leapt at the chance to take advantage of these new opportunities.

The biological turn in materials science has led to career trajectories that would have seemed outrageous in the twentieth century. A good example is Henry Hess, currently a professor in the Biomedical Engineering department in Columbia University's School of Engineering and Applied Science (both "biomedical engineering" and "school of engineering and applied science" are themselves telling signs of the times).[73] Hess's PhD was in physics. He then took a postdoc in the bioengineering department at the University of Washington, working for Viola Vogel, a prominent figure in the ascendance of biomaterials research. After that, he became an assistant professor in the materials science and engineering department at the University of Florida before taking his current post. He was also editor-in-chief of the Institute of Electrical and Electronics Engineers' *Transactions on NanoBioScience*. In one person, we see the melding of electrical engineering, biomedical engineering, materials science, physics, and nanotechnology.

What kind of research could qualify one for jobs in all these different disciplines? Hess is best known for taking the molecules involved in motion in living cells, for instance muscles or bacteria—and adapting them as stand-alone "machines." He can take the protein kinesin and "train" it to walk in a circle around a surface. One could imagine applications in microelectronics (using the kinesin or something like it either to construct circuit components or even to carry information itself), in pharmaceuticals (the kinesin could carry a drug molecule to where it was needed), or prosthetics (large arrays of kinesin or something similar could convert chemical energy into motion in a manner analogous to natural muscle). What is perhaps most intriguing for the future of the concept of "materials" is the ambiguity inherent in the idea of "large arrays" of engineered biochemical systems. An individual kinesin walking around is not a material; but a large array might be.

---

[71] Kevles, "Big Science."

[72] Hughes, *Genentech*.

[73] Hess is an accomplished scientist but hardly an isolated example. We use him here as a token of changes in materials science and in the possible career paths of scientists in fields adjoining materials science.

Materials science in the 2020s, therefore, looks quite different from the commanded interdiscipline of the 1960s from one angle (more disciplines, more materials, more patrons, more applications), but quite similar to it from another. Rather than focusing on alloys and semiconductors to address the challenges of a struggle for global military superiority, it investigates nano- and biomaterials—and, more recently, one-dimensional materials like graphene—driven by their relevance to a globalized economy. At the same time, however, it remains an interdiscipline whose content is defined by era-specific challenges, and which derives its stability from the institutions and networks that support it.

BIBLIOGRAPHY

Belanger, Dian Olson. *Enabling American Innovation: Engineering and the National Science Foundation*. West Lafayette, IN: Purdue University Press, 1998. (Link to IsisCB)

Bensaude-Vincent, Bernadette. "The Concept of Materials in Historical Perspective." *NTM Zeitschrift für Geschichte der Wissenschaften, Technik und Medizin* 19, no. 1 (2011): 107–23. (Link to IsisCB)

Bensaude-Vincent, Bernadette. "The Construction of a Discipline: Materials Science in the United States." *Historical Studies in the Physical and Biological Sciences* 31, no. 2 (2001): 223–48. (Link to IsisCB)

Bloom, Justin L., and Shinsuke Asano. "Tsukuba Science City: Japan Tries Planned Innovation." Science 202, no. 4500 (1981): 1239–47.

Bursten, Julia R. S. "Computer Simulations." In *Between Making and Knowing: Tools in the History of Materials Research*, WSPC Encyclopedia of the Development and History of Materials Science, vol. 1, edited by Joseph D. Martin and Cyrus C. M. Mody, 195–206. Singapore: World Scientific, 2020.

Bush, Vannevar. *Science—The Endless Frontier*. Washington, DC: United States Government Printing Office, 1945.

Cahn, Robert W. *The Coming of Materials Science*. Amsterdam: Pergamon, 2001. (Link to IsisCB)

Choi, Hyungsub, and Brit Shields. "A Place for Materials Science: Laboratory Buildings and Interdisciplinary Research at the University of Pennsylvania." *Minerva* 53, no. 1 (2015): 21–42. (Link to IsisCB)

Committee on the Survey of Materials Science and Engineering (COSMAT). *Materials and Man's Needs*, 4 vols. Washington, DC: National Academy of Sciences, 1975.

Committee on the Survey of Materials Science and Engineering (COSMAT). *Materials and Man's Needs: Materials Science and Engineering: Summary Report of the Committee on the Survey of Materials Science and Engineering*. Washington, DC: National Academy of Sciences, 1974.

Crease, Robert P., and Catherine Westfall. "The New Big Science." *Physics Today* 65, no. 5 (2016): 30–36.

Daniels, Mario, and John Krige. "Beyond the Reach of Regulation?: 'Basic' and 'Applied' Research in the Early Cold War United States." *Technology and Culture* 59, no. 2 (2018): 226–50. (Link to IsisCB)

Doing, Park. *Velvet Revolution at the Synchrotron: Biology, Physics, and Change in Science*. Cambridge, MA: MIT Press, 2009. (Link to IsisCB)

Edgerton, David. "The Linear Model Did Not Exist." In *The Science-Industry Nexus: History, Policy Implications*, edited by Karl Grandin, Nina Wormbs, and Sven Widmalm, 31–58. Sagamore Beach, MA: Watson Publishing International, 2004. (Link to IsisCB)

Eisler, Matthew N. "'The Ennobling Unity of Science and Technology': Materials Sciences and Engineering, the Department of Energy, and the Nanotechnology Enigma." *Minerva* 51, no. 2 (2013), 225–51. (Link to IsisCB)

Forman, Paul. "On the Historical Forms of Knowledge Production and Curation: Modernity Entailed Disciplinarity, Postmodernity Entails Antidisciplinarity." *Osiris* 27 (2012): 56–97. (Link to IsisCB)

Galison, Peter. "The Americanization of Unity." *Daedalus* 127, no. 1 (1998): 45–71. (Link to IsisCB)

Godin, Benoît. "The Linear Model of Innovation: The Historical Construction of an Analytical Framework." *Science, Technology, and Human Values* 31, no. 6 (2006): 639–67.

Godin, Benôit. *Models of Innovation: The History of an Idea*. Cambridge, MA: MIT Press, 2017. (Link to IsisCB)

Golinski, Jan. *Making Natural Knowledge: Constructivism and the History of Science*. Chicago: University of Chicago Press, 1998. (Link to IsisCB)

Gribbe, Johan, and Olof Hallonsten. "The Emergence and Growth of Materials Science in Swedish Universities." *Historical Studies in the Natural Sciences* 47, no. 4 (2017): 459–93.

Groenewegen, Peter, and Lois Peters. "The Emergence and Change of Materials Science and Engineering in the United States." *Science, Technology, and Human Values* 27, no. 1 (2002), 112–33. (Link to IsisCB)

Hallonsten, Olof, and Thomas Kaiserfeld. "Neutron Sources." In *Between Making and Knowing: Tools in the History of Materials Research*, edited by Joseph D. Martin and Cyrus C. M. Mody. WSPC Encyclopedia of the Development and History of Materials Science, vol. 1., 553–60. Singapore: World Scientific, 2020.

Hallonsten, Olof. "The Parasites: Synchrotron Radiation at SLAC, 1972–1992." *Historical Studies in the Natural Sciences* 45, no. 2 (2014): 217–72. (Link to IsisCB)

Hartman, Paul. *Cornell's Materials Science Center: The Early Years*. Ithaca, NY: Cornell Center for Materials Research, 2007.

Heinze, Thomas, Olof Hallonsten, and Steffi Heinecke. "From Periphery to Center: Synchrotron Radiation at DESY." Pts. 1 and 2, "Part I: 1962–1977," "Part II: 1977–1993." Historical Studies in the Natural Sciences 45, no. 3 (2015): 447–92; no. 4 (2015): 513–48. (Link to IsisCB)

Heinze, Thomas, Olof Hallonsten, and Steffi Heinecke. "Turning the Ship: The Transformation of DESY, 1993–2009." *Physics in Perspective* 19, no. 4 (2017): 424–51.

Hentschel, Klaus. "Von der Materialforschung zur *Materials Science*," *NTM Zeitschrift für Geschichte der Wissenschaften, Technik und Medizin* 19, no. 1 (2011): 5–40. (Link to IsisCB)

Hornbogen, Erhard. *Aufbau und Eigenschaften*. Berlin: Springer, 1973.

Horowitz, Emanuel, and John L. Torgesen. *Biomaterials: Proceedings of a Symposium Held in Conjunction with the Ninth Annual Meeting of the Association for the Advancement of Medical Instrumentation, New Orleans, April 19–20, 1974*. Washington, DC: National Bureau of Standards, 1974.

Huebsch, Nathaniel, and David J. Mooney. "Inspiration and Application in the Evolution of Biomaterials." *Nature* 462, no. 7272 (2009): 426–32.

Hunt, Bruce J. *Pursuing Power and Light: Technology and Physics from James Watt to Albert Einstein*. Baltimore: Johns Hopkins University Press, 2010. (Link to IsisCB)

Huggins, Robert A. "Accomplishments and Prospects of the Interdisciplinary Laboratories," in *Problems and Issues of a National Materials Policy: Papers Delivered at an Engineering Foundation Research Conference on National Materials Policy, July 1970*, 221–35. Washington, DC: US Government Printing Office, 1970.

Hughes, Sally Smith. *Genentech: The Beginnings of Biotech.* Chicago: University of Chicago Press, 2011. (Link to IsisCB)

James, Jeremiah, Thomas Steinhauser, Dieter Hoffmann, and Bretislav Friedrich. *One Hundred Years at the Intersection of Chemistry and Physics: The Fritz Haber Institute of the Max Planck Society 1911–2011*. Berlin: de Gruyter, 2011.

Josephson, Paul R. *Red Atom: Russia's Nuclear Power Program from Stalin to Today*. Pittsburgh: University of Pittsburgh Press, 2005. (Link to IsisCB)

Josephson, Paul. "Soviet Scientists and the State: Politics, Ideology, and Fundamental Research from Stalin to Gorbachev." *Social Research* 59, no. 3 (1992): 589–614. (Link to IsisCB)

Josephson, Paul, and Aleksandr Sorokin. "Physics Moves to the Provinces: The Siberian Physics Community and Soviet Power, 1917–1940 (2017)." *British Journal for the History of Science* 50, no. 2 (2017): 297–327. (Link to IsisCB)

Kaiser, David. "The Atomic Secret in Red Hands?: American Suspicions of Theoretical Physicists during the Early Cold War." *Representations* 90, no. 1 (2005): 28–60. (Link to IsisCB)

Kaiser, David. "From Blackboards to Bombs." *Nature* 523, no. 7562 (2015): 523–25.

Kevles, Daniel J. "Big Science and Big Politics in the United States: Reflections on the Death of the SSC and the Life of the Human Genome Project." *Historical Studies of the Physical and Biological Sciences* 27, no. 2 (1997): 269–97. (Link to IsisCB)

Kevles, Daniel J. *The Physicists: The History of a Scientific Community in Modern America*, 3rd ed. 1971. Reprint, Cambridge, MA: Harvard University Press, 1995. (Link to IsisCB)

Kline, Ronald. *The Cybernetics Moment, or: Why We Call Our Age the Information Age*. Baltimore: Johns Hopkins University Press, 2015. (Link to IsisCB)

Krige, John. *American Hegemony and the Postwar Reconstruction of Science in Europe*. Cambridge, MA: MIT Press, 2006. (Link to IsisCB)

Leslie, Stuart W. *The Cold War and American Science: The Military-Industrial-Academic Complex at Stanford and MIT*. New York: Columbia University Press, 1993. (Link to IsisCB)

Leslie, Stuart W. "Profit and Loss: The Military and MIT in the Postwar Era." *Historical Studies in the Physical and Biological Sciences* 21, no. 1 (1990): 59–85. (Link to IsisCB)

Lyman (Richard W.), President of Stanford University, Papers. Department of Special Collections and University Archives, Stanford University Libraries, Stanford, CA.

Martin, Joseph D. *Solid State Insurrection: How the Science of Substance Made American Physics Matter* (Pittsburgh: University of Pittsburgh Press, 2018). (Link to IsisCB)

Martin, Joseph D. "What's in a Name Change?: Solid State Physics, Condensed Matter Physics, and Materials Science." *Physics in Perspective* 17, no. 1 (2015): 3–32. (Link to IsisCB)

Martin, Joseph D., and Cyrus C. M. Mody, eds. *Between Making and Knowing: Tools in the History of Materials Research*, WSPC Encyclopedia of the Development and History of Materials Science, vol. 1. Singapore: World Scientific, 2020.

Materials Advisory Board, Committee on Characterization of Materials. *Characterization of Materials*, Publication MAB-229-M. Washington, DC: National Academy of Sciences, 1967.

Mercelis, Joris. *Beyond Bakelite: Leo H. Baekeland (1863–1944) and the Business of Science and Invention* (Cambridge, MA: MIT Press, 2020).

Merz, Martina, and Peter Biniok. "The Local Articulation of Contextual Resources: From Metallic Glasses to Nanoscale Research." In *The Local Configuration of New Research Fields: On Regional and National Diversity*, edited by Martina Merz and Philippe Sormani, 99–116. Cham: Springer, 2016.

Misa, Thomas J. *A Nation of Steel: The Making of Modern America, 1865–1925.* Baltimore, MD: Johns Hopkins University Press, 1998. (Link to IsisCB)

Mody, Cyrus C. M. *Instrumental Community: Probe Microscopy and the Path to Nanotechnology*. Cambridge, MA: MIT Press, 2011. (Link to IsisCB)

Mody, Cyrus C. M. *The Long Arm of Moore's Law: Microelectronics and American Science*. Cambridge, MA: MIT Press, 2017. (Link to IsisCB)

Mody, Cyrus C. M., and Hyungsub Choi. "From Materials Science to Nanotechnology: Interdisciplinary Center Programs at Cornell University, 1960–2000." *Historical Studies in the Natural Sciences* 43, no. 2 (2013): 121–61. (Link to IsisCB)

Morris, Peter J. T. "Sites and Technology." In *A Cultural History of Chemistry*, edited by Peter J. T. Morris and Alan J. Rocke. London: Bloomsbury, forthcoming.

National Academy of Sciences. *Advancing Materials Research*. Washington, DC: National Academies Press, 1987.

National Academy of Sciences. More Effective Organization and Administration of Materials Research and Development: A Report to Detlev W. Bronk, President, National Academy of Sciences, by the Committee on Scope and Conduct of Materials Research. Washington, DC: National Academy of Sciences, 1960.

Nelson, Andrew J. "Cacophony or Harmony? Multivocal Logics and Technology Licensing by the Stanford University Department of Music." *Industrial and Corporate Change* 14, no. 1 (2005): 93–119.

Nordmann, Alfred. “Invisible Origins of Nanotechnology: Herbert Gleiter, Materials Science, and Questions of Prestige.” *Perspectives on Science* 17 no. 2 (2009): 123–43. (Link to IsisCB)

Phillips, Julia M. “The Founding of the MRS—The Rise of Interdisciplinarity.” *MRS Bulletin* 41 (2016): 339–40.

Plummer, John. “Metallurgy Is Key.” *Nature Materials* 15 (2016): 699–700.

Pollock, Ethan. *Stalin and the Soviet Science Wars*. Princeton: Princeton University Press, 2006. (Link to IsisCB)

Renn, Jürgen et al., “Research Program History of the Max Planck Society, Report 2014–2017.” http://gmpg.mpiwg-berlin.mpg.de/media/cms_page_media/2/Research Report 2014–2017.pdf.

Rohrer, Heinrich. “STM: 10 Years after.” *Ultramicroscopy* 42 (1992): 1-6.

Rush, John J. “US Neutron Facility Development in the Last Half-Century: A Cautionary Tale.” *Physics in Perspective* 17, no. 2 (2015): 135–55. (Link to IsisCB)

Sachse, Carola. “Basic Research in the Max Planck Society.” In *Basic and Applied Research: The Language of Science Policy in the Twentieth Century*, edited by David Kaldewey and Desirée Schauze, 163–86. New York: Berghahn, 2018. (Link to IsisCB)

Schwartz, Rebecca Press. “The Making of the History of the Atomic Bomb: Henry Dewolf Smyth and the Historiography of the Manhattan Project.” PhD diss., Princeton University, 2008. (Link to IsisCB)

Schatzberg, Eric. “Ideology and Technical Choice: The Decline of the Wooden Airplane in the United States, 1920–1945.” *Technology and Culture* 35, no. 1 (1994): 34–69. (Link to IsisCB)

Smith, Cyril Stanley. “Matter versus Materials: A Historical View.” *Science* 162, no. 3854 (1968): 637–44.

Stanford University Sponsored Projects Office Collection, SC344, ACCN1986-200. Department of Special Collections and University Archives, Stanford University Libraries, Stanford, CA.

Teissier, Pierre. “Solid-State Chemistry in France: Structures and Dynamics of a Scientific Community since World War II.” *Historical Studies in the Natural Sciences* 40, no. 2, (2010): 225–58. (Link to IsisCB)

Travis, Anthony S. “Modernizing Industrial Organic Chemistry: Great Britain between Two World Wars.” In *Determinants in the Evolution of the European Chemical Industry, 1900–1939*, edited by Anthony S. Travis, Harm G. Schröter, Ernst Homburg, and Peter J. T. Morris, 171–98. Dordrecht: Springer, 1998.

Van Vlack, Lawrence H. *Elements of Material Science and Engineering*. Reading, MA: Addison-Wesley, 1959.

York, Emily. “Nano Dreams and Nanoworlds: *Fantastic Voyage* as a Fantastic Origin Story.” *Configurations* 23, no. 3 (2015): 263–99. (Link to IsisCB)

Zadpoor, Amir A. “The Evolution of Biomaterials Research.” *Materials Today* 16, no. 11 (2013): 408–9.